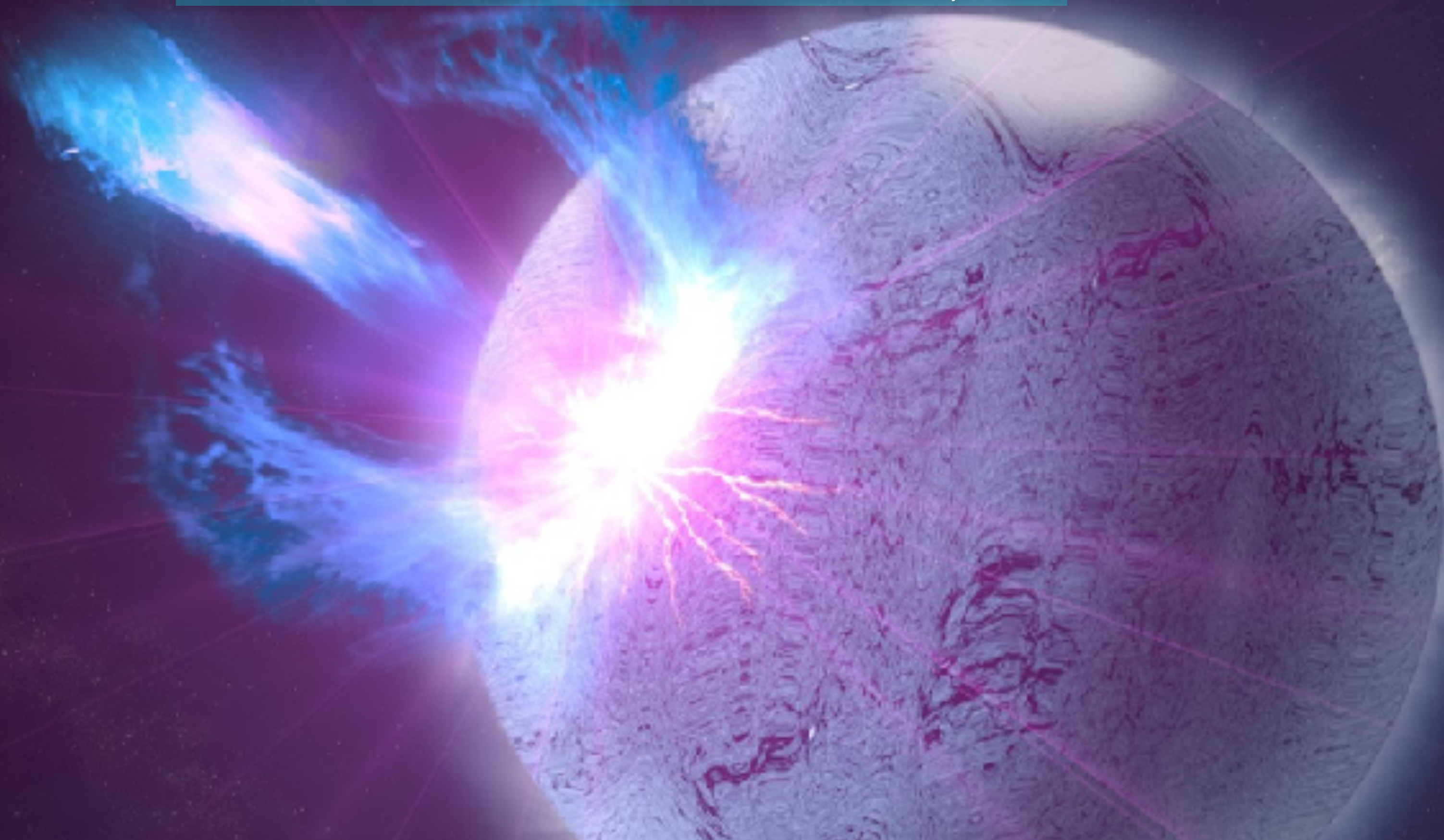
FRBs from Low-twist Magnetars

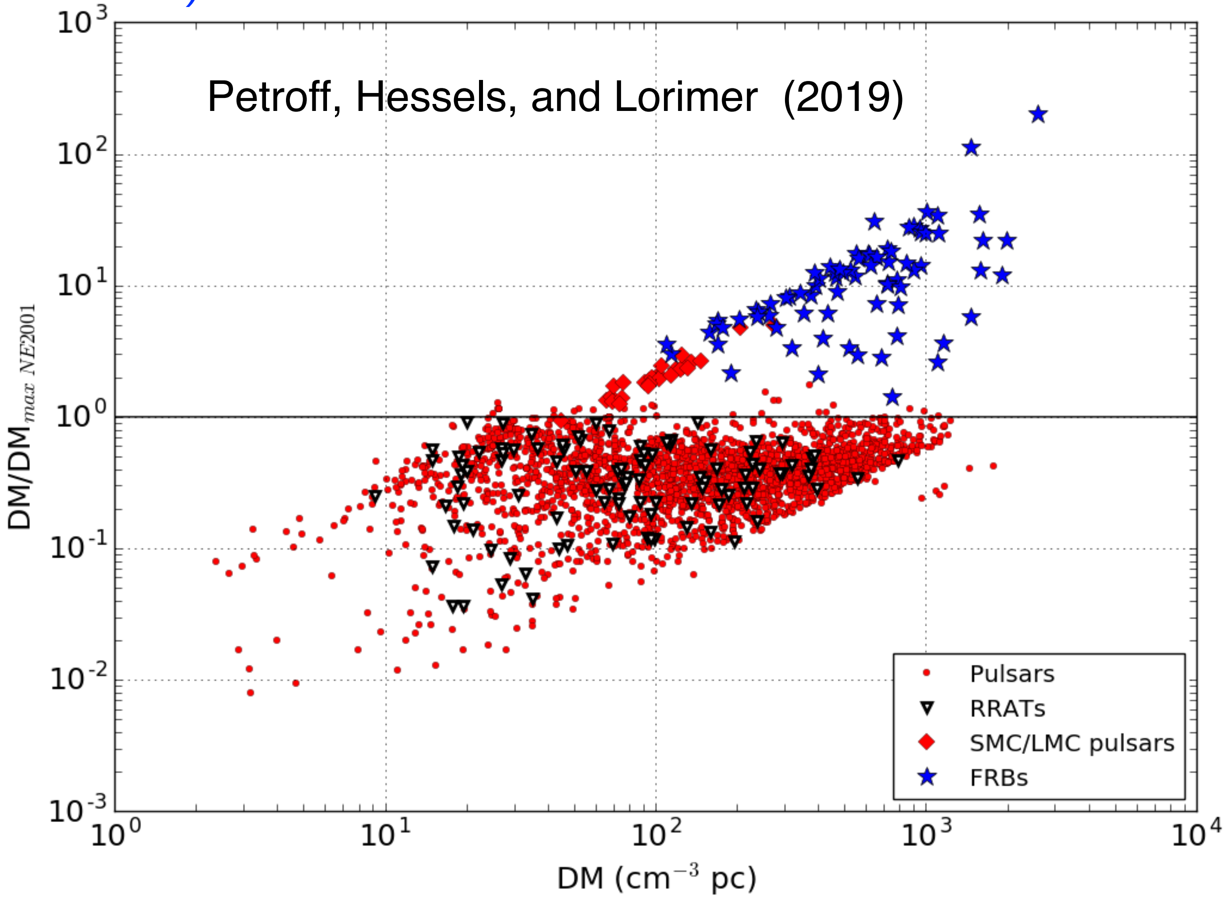
(based on Wadiasingh and Timokhin 2019, accepted to ApJ, arxiv: 1904.12036)



Zorawar Wadiasingh (NASA/GSFC)
Andrey Timokhin (NASA/GSFC)

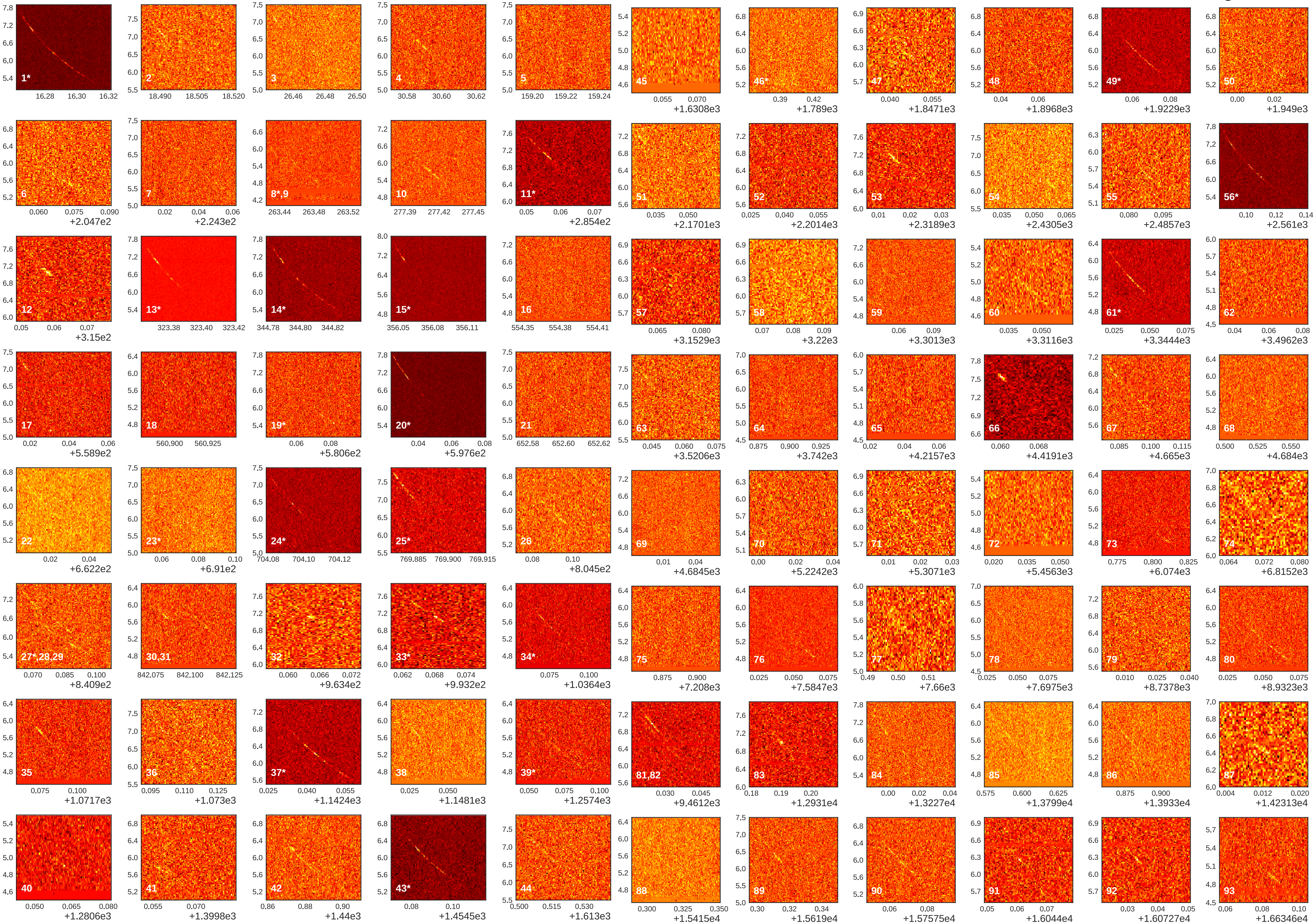
Fast Radio Bursts

- Extragalactic pulses of observed 1-50 ms duration
- "coherent" with brightness $T \gg 10^{30}$ K
- Multiple repeaters - FRB 121102 and CHIME repeater(s)
- Isotropic equivalent energy of $>10^{37}$ erg
- Some exhibit high polarization (some linear, some circular, FRB 121102 is 100% linearly polarized)



FRB 121102 — 93 GBT bursts (4-8 GHz) on August 6, 2017

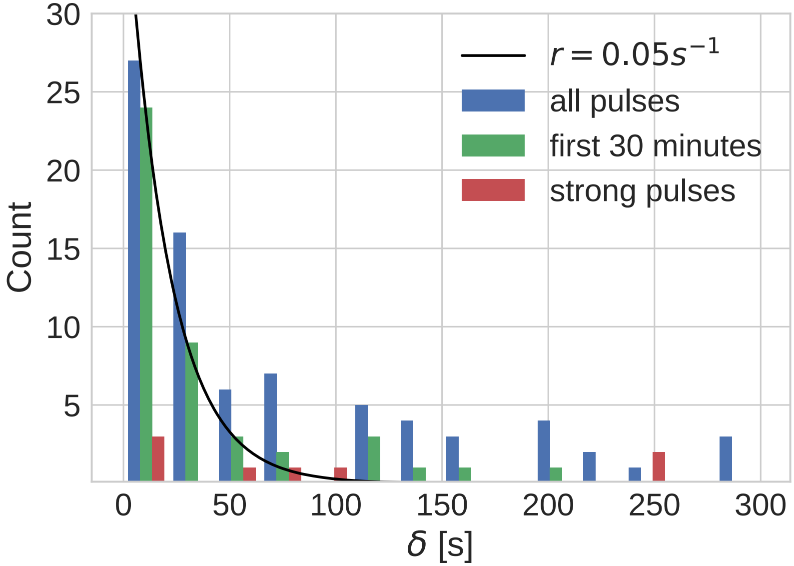
Zhang+ 2018



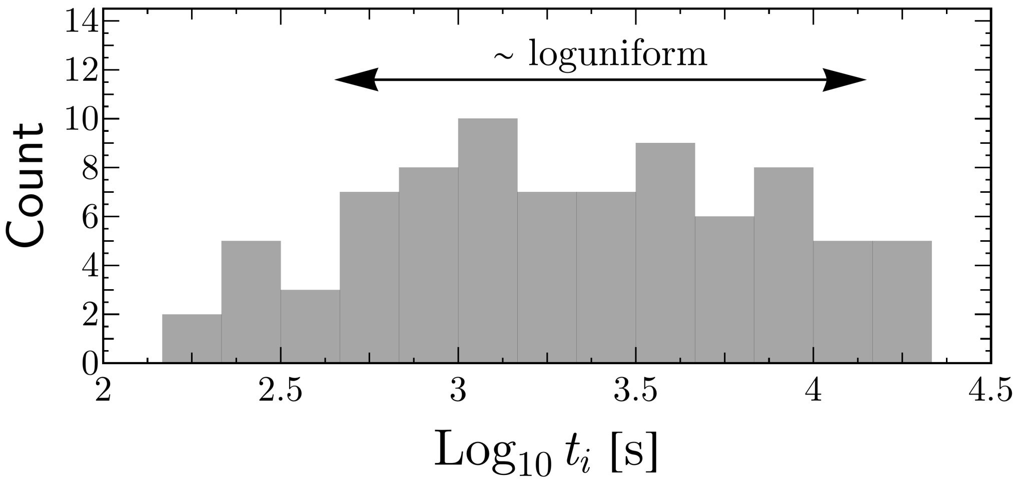
Arrival times are non-Poissonian

Arrival times of pulses are independent of the emission mechanism, and probe the trigger in the progenitor

Zhang+ (2018)



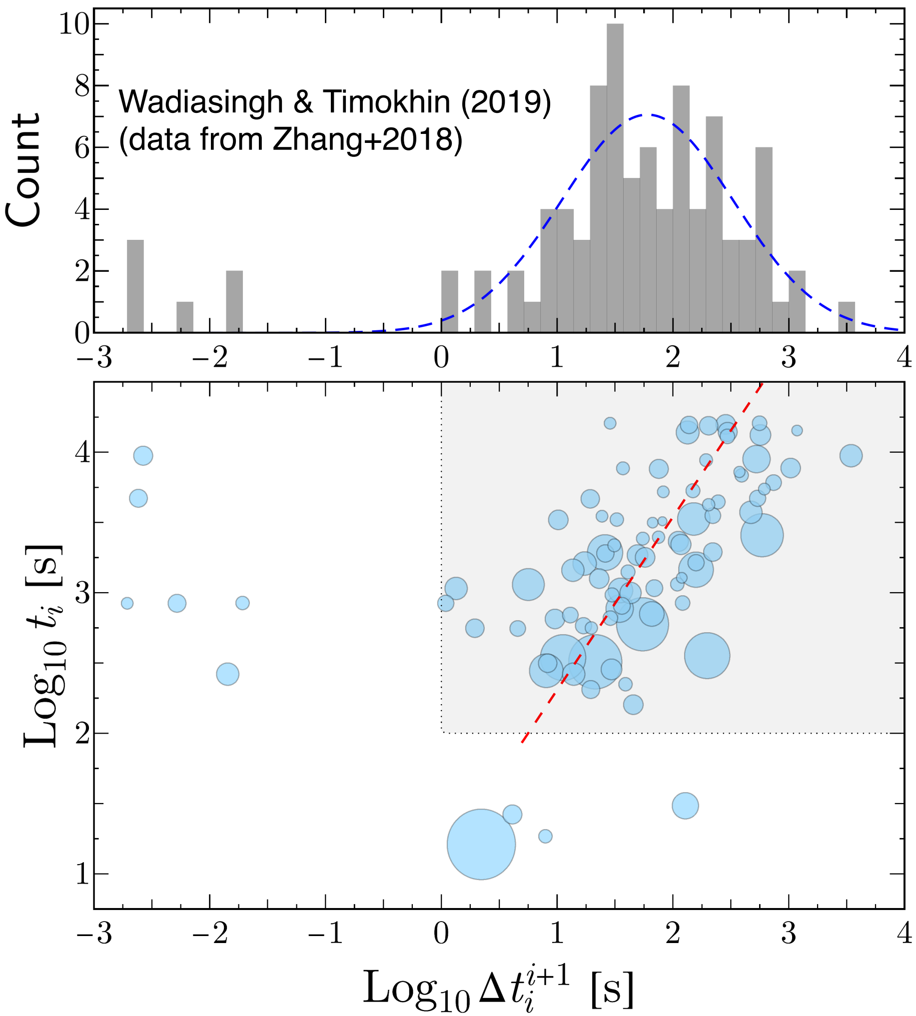
Wadiasingh & Timokhin (2019)
(data from Zhang+ 2018)



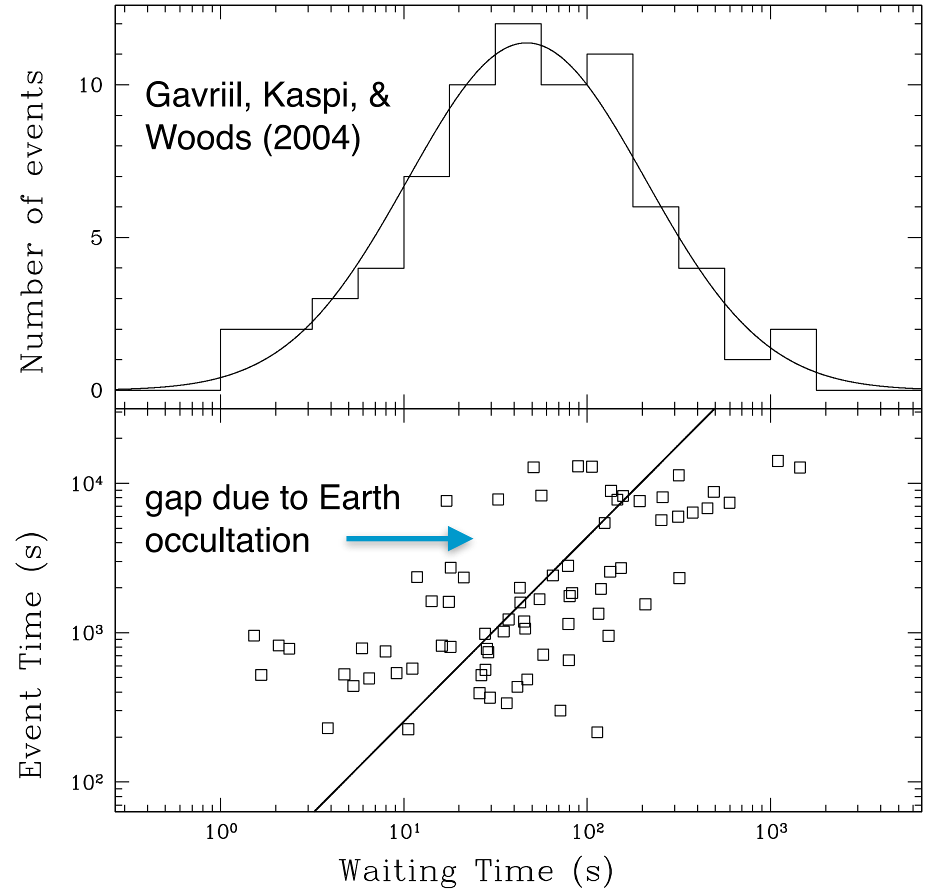
Log character of arrival times suggestive of multiplicative trigger with "memory" of previous events or states
$\rightarrow$ "sandpiles", earthquakes and reconnection-like processes

FRBs and “Magnetar Short Bursts”

FRB 121102 — 93 GBT bursts on August 6, 2017



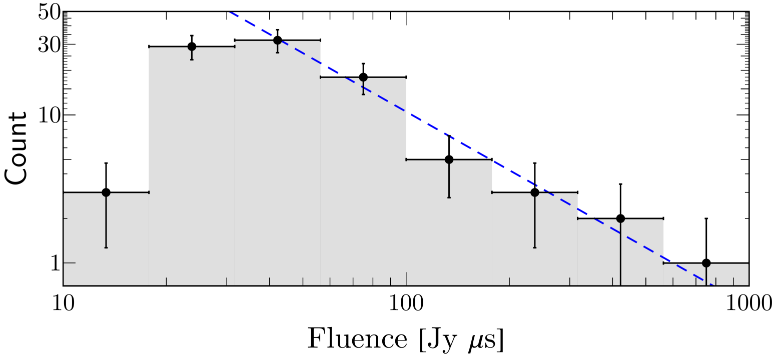
Magnetar 1E 2259+586, 80 RXTE shorts bursts on June 18, 2002



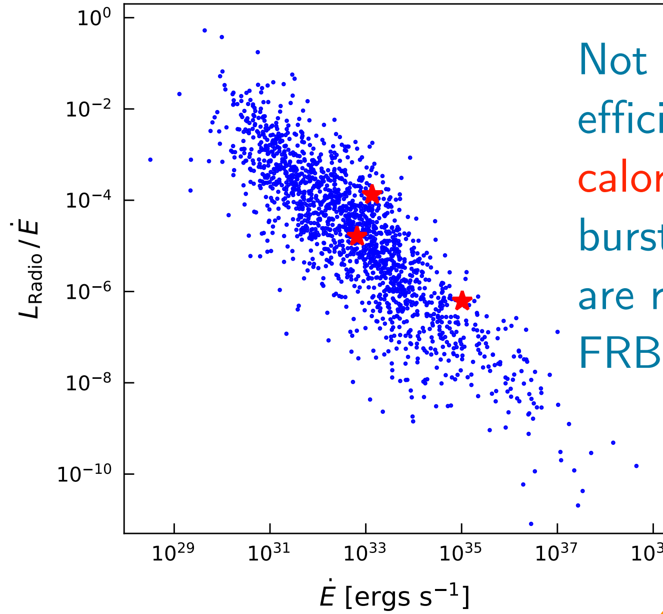
$\Delta t \simeq 0.1\, t^{0.8}$ for both!

Power-law Fluence/Luminosity Distributions

FRB 121102 — 93 GBT bursts

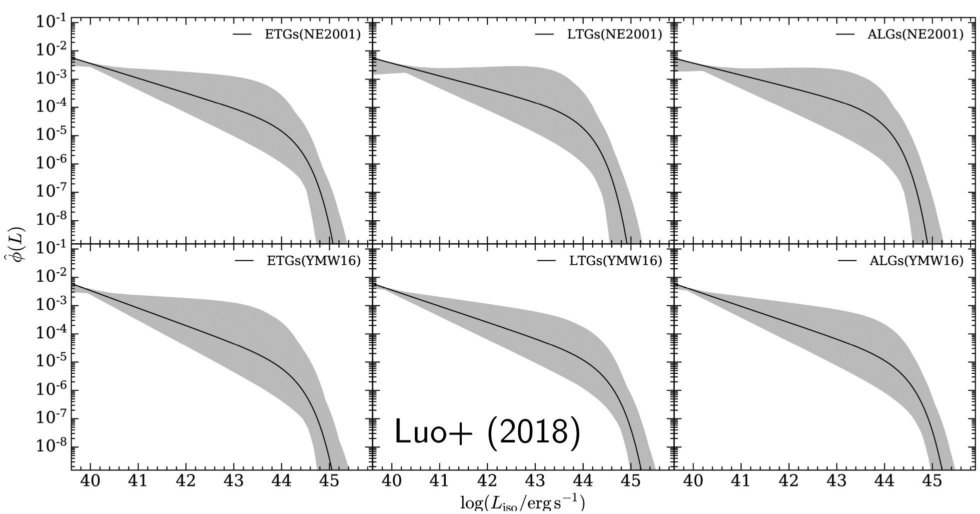


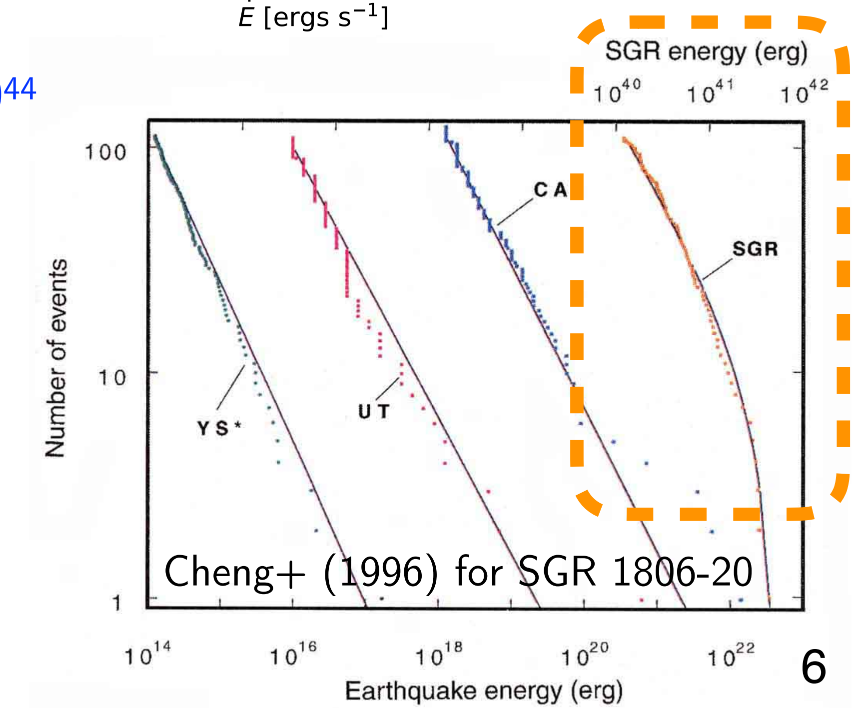
$$\mathcal{E}_{\rm iso} \lesssim 3 \times 10^{39} \left(\frac{\mathcal{F}}{600\,\mathrm{Jy}\,\mu\mathrm{s}}\right)\left(\frac{\Delta W}{4\,\mathrm{GHz}}\right)\left(\frac{d_L}{1\,\mathrm{Gpc}}\right)^2 \quad \mathrm{erg}.$$



Not implausible radio efficiencies of the calorimetric short burst energy release are required for the FRB

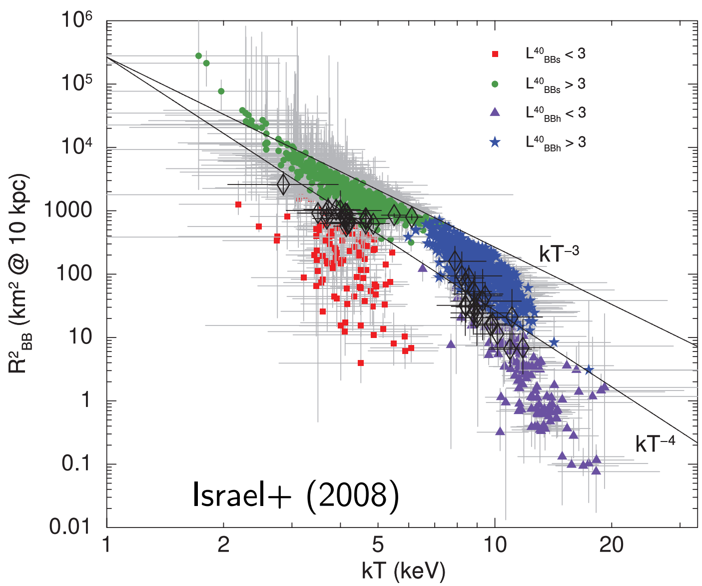
High energy cutoff of about 10^{41}-10^{42} erg (10^{44} erg/s) in the luminosity function of FRBs

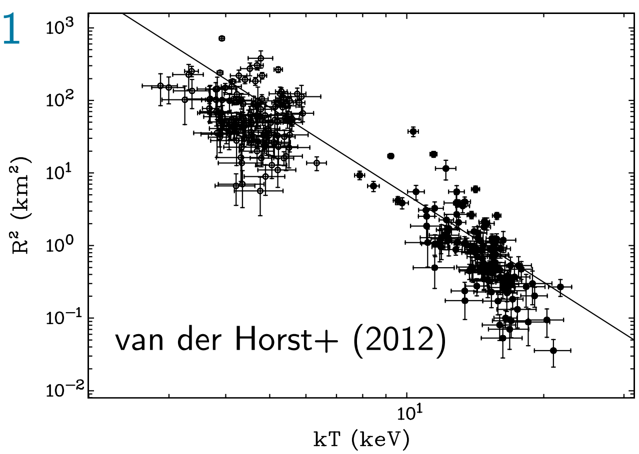


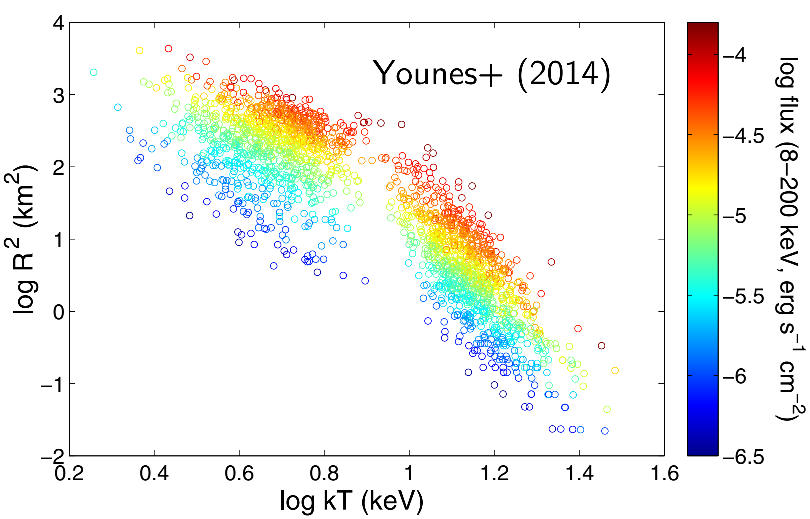


What are magnetar short bursts?

- $\sim$10 - 500 ms duration, typically 100 ms, with shorter rise time
- In any given burst, evidence of hot and cool BBs with vastly different emission areas but similar luminosity $R^2 \sim T^{-4}$
- $\rightarrow$ implies coupling in the closed field line zone of the magnetosphere, and confinement
- Hot BB with small area = magnetic footpoints and return currents
- Cool BB with large area = thermalized pair plasma in the flux tube
- Burst energetics are low enough such that magnetic dominance should be maintained in a magnetar, i.e. $\sigma \gg 1$







What are magnetar short bursts?

- QPOs (~0.1 kHz) associated with crustal-torsional oscillations strongly suggest short bursts occur at very low altitudes and are associated with the NS crust
- Such crustal oscillations damp on a timescale of ∼1-2 s due to core-crust coupling (e.g. Levin 2006)

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QUASI-PERIODIC OSCILLATIONS IN SHORT RECURRING BURSTS OF MAGNETARS SGR 1806−20 AND SGR 1900+14 OBSERVED WITH *RXTE*

D. HUPPENKOTHEN[1], L. M. HEIL[1], A. L. WATTS[1], AND E. GÖĞÜŞ[2]
[1] Anton Pannekoek Institute for Astronomy, University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, The Netherlands; D.Huppenkothen@uva.nl
[2] Sabanci University, Orhanli-Tuzla, İstanbul 34956, Turkey
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QUASI-PERIODIC OSCILLATIONS IN SHORT RECURRING BURSTS OF THE SOFT GAMMA REPEATER J1550−5418

D. HUPPENKOTHEN[1], C. D'ANGELO[1], A. L. WATTS[1], L. HEIL[1], M. VAN DER KLIS[1], A. J. VAN DER HORST[1], C. KOUVELIOTOU[2,3], M. G. BARING[4], E. GÖĞÜŞ[5], J. GRANOT[6], Y. KANEKO[5], L. LIN[7], A. VON KIENLIN[8], AND G. YOUNES[3,9]
[1] Astronomical Institute "Anton Pannekoek," University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, The Netherlands; D.Huppenkothen@uva.nl
[2] Astrophysics Office, ZP 12, NASA-Marshall Space Flight Center, Huntsville, AL 35812, USA
[3] NSSTC, 320 Sparkman Drive, Huntsville, AL 35805, USA
[4] Department of Physics and Astronomy, Rice University, MS-108, P.O. Box 1892, Houston, TX 77251, USA
[5] SabancıUniversity, Orhanlı-Tuzla, İstanbul 34956, Turkey
[6] Department of Natural Sciences, The Open University of Israel, 1 University Road, P.O. Box 808, Ra'anana 43537, Israel
[7] François Arago Centre, APC, 10 rue Alice Domon et Léonie Duquet, F-75205 Paris, France
[8] Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse 1, D-85748 Garching, Germany
[9] Universities Space Research Association, 6767 Old Madison Pike, Suite 450, Huntsville, AL 35806, USA
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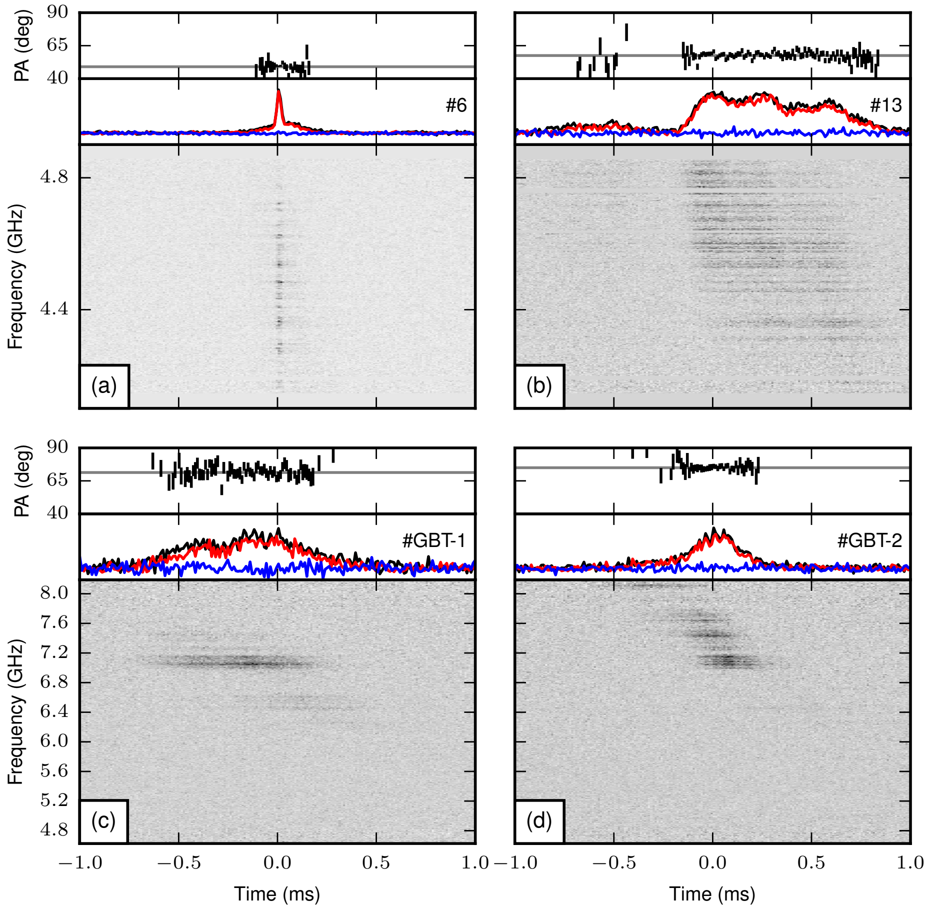
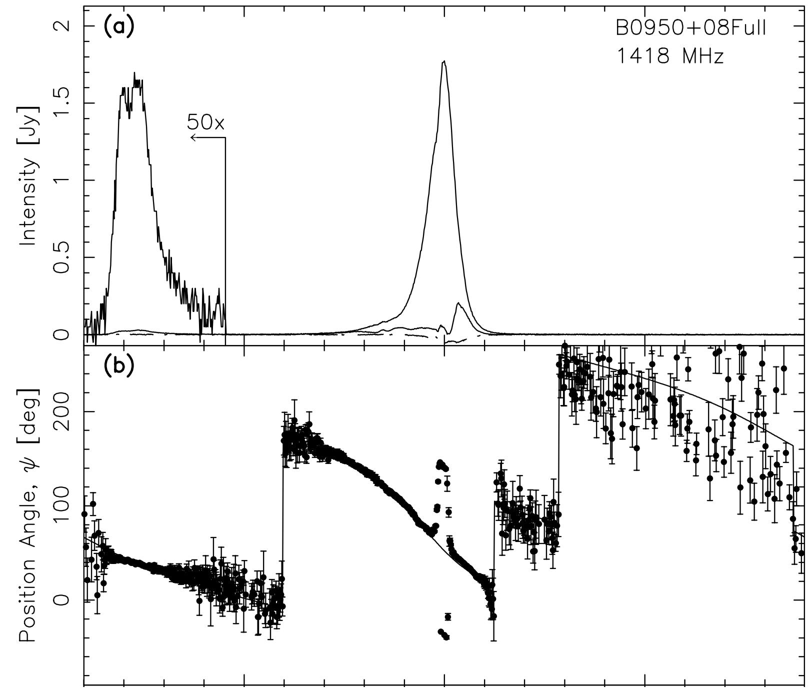
FRB 121102's NS must not be a fast rotator

FRB 121102 — 100% linearly polarized with PA fixed during a burst and modestly varying between bursts



Michilli+ (2018)

Contrast: PA swings during pulses of radio pulsars from polar cap emission



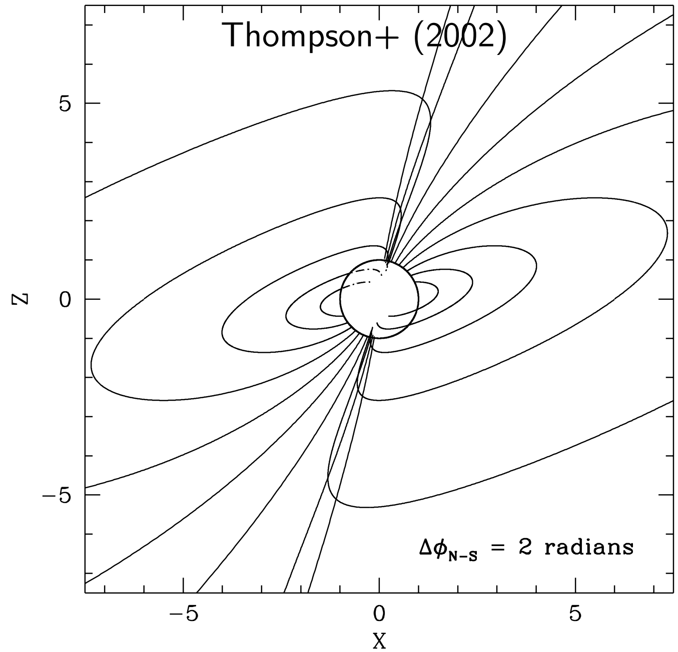
Everett and Weisberg (2001)

Twisted Magnetospheres

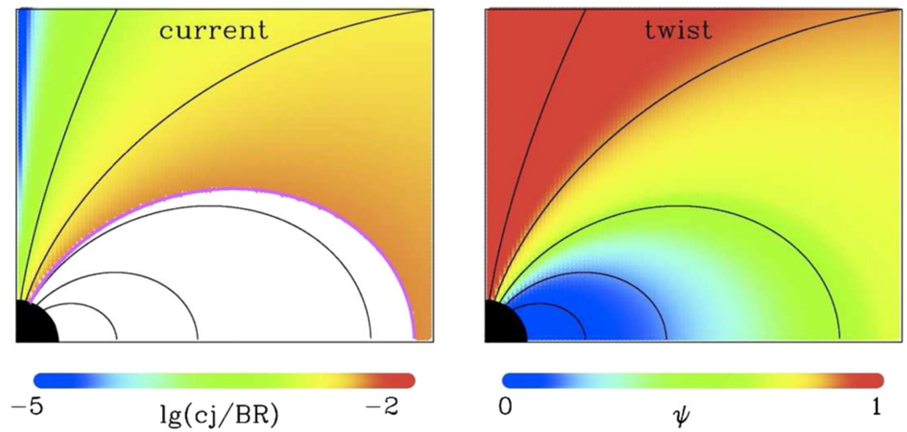
- Known galactic magnetars must have modestly twisted magnetospheres to support persistent emission
- A current system is set up to support the twist:

$$\frac{e n_e}{|\rho_{\rm GJ}|} \approx \frac{4{,}670}{\epsilon_{\rm rad}\langle\gamma_e\rangle}\,\frac{L_{\rm X,35}\,P}{B_{15}\,R_6^2}$$

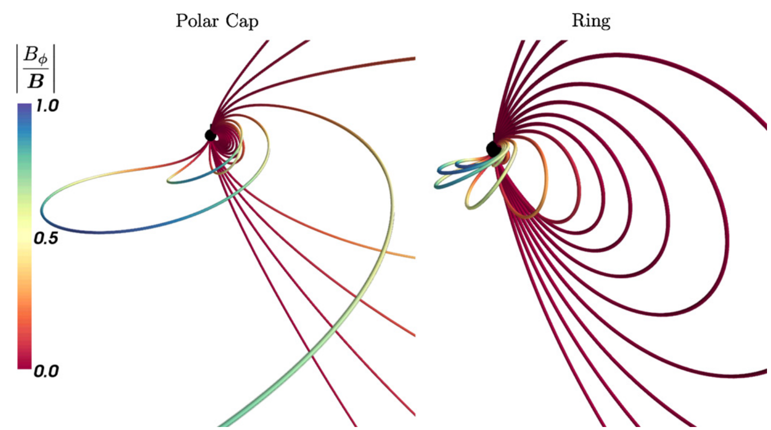
Baring & Harding (2007)



Beloborodov (2013)



Parfrey+ (2013)



$$j_{\rm twist} = \frac{c}{4\pi}\,|\boldsymbol{\nabla}\times\boldsymbol{B}| \sim \frac{c}{4\pi}\frac{B}{R_*}\,\sin^2\theta_0\,\Delta\phi$$

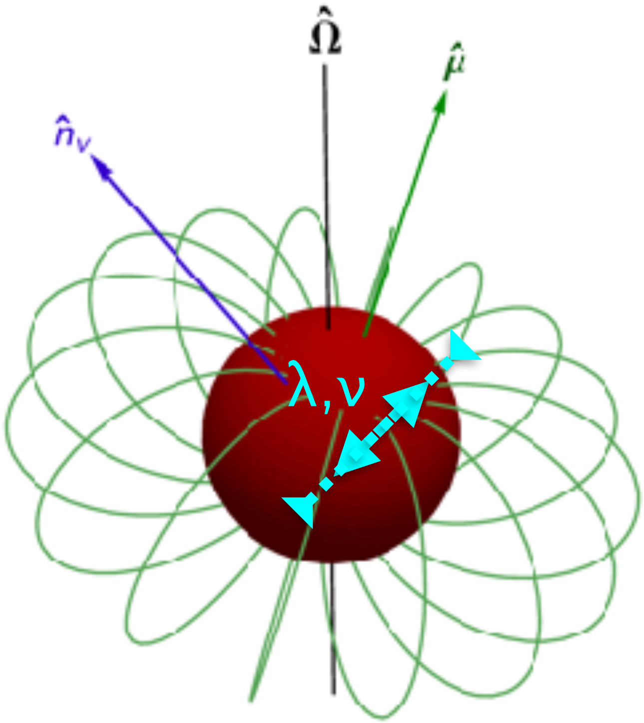
$$\rho_{\rm twist} \sim j_{\rm twist}/c$$

$$\rho_{\rm GJ} \sim \frac{B}{cP}$$

$$\boxed{\rho_{\rm twist} \gg \rho_{\rm GJ}}$$

FRBs from crustal dislocations

- If crustal dislocations occur with wavelength $\lambda \sim 10^4$ cm at a frequency $\nu \sim 0.1$-1 kHz, and if the charge density is sufficiently high, the energy is dissipated by a plasma wave interactions and fluid-like processes (E immediately screened)



$$E \sim \frac{v}{c} B \sim \frac{2\pi\nu\xi}{c} B$$

ν set by the characteristic kHz scale of observed QPOs

$$\rho_{\rm burst} \sim \frac{1}{4\pi}\frac{E}{\lambda} \sim \frac{1}{2}\frac{\xi}{\lambda}\frac{\nu}{c}B$$

If the charge density is low, however, intense particle acceleration and pair cascades must occur to satisfy the current demanded by the field dislocation(s)

$$\boxed{\rho_{\rm burst} > \max\{\rho_{\rm twist}, \rho_{\rm GJ}\}}$$

This is a necessary (but not sufficient) condition for FRBs in this model

$$\text{(yielding) strain}: \ \sigma \equiv \frac{\Delta x}{x} \sim \frac{\xi}{\lambda} \sim 10^{-3} - 10^{-2}$$

From the condensed matter physics of NS crusts

Conditions for FRBs from magnetar short bursts

$$\boxed{\rho_{\rm burst} > \max\{\rho_{\rm twist}, \rho_{\rm GJ}\}}$$

- Most (>50%) FRBs ought to yield short bursts, but not all short bursts should result in FRBs
- $\rightarrow$ slow rotator with low magnetospheric twist
- Duration of FRB pulses set by characteristic plasma-filling time of flux tubes

$$\Delta\phi \lesssim \frac{2\pi R_*}{c}\nu\frac{1}{\sin^2\theta_0}\frac{\xi}{\lambda} \simeq 0.003\,\nu_{\rm kHz}\;\sigma_{-3}$$

Low-twist condition (independent of B!)

$$P \gtrsim \frac{2}{\nu_{\rm kHz}\sigma_{-3}} \quad {\rm sec}$$

Slow rotator condition ($\Delta\phi = 0$)

$$\xi \gtrsim \frac{2\lambda}{\nu P} \approx 2\frac{\lambda_4}{\nu_{\rm KHz}P_{10\ {\rm s}}} \quad {\rm cm}$$

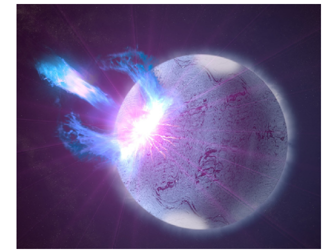
Threshold amplitude $\rightarrow$ implies lower bound to FRB energy/luminosity function for a given P

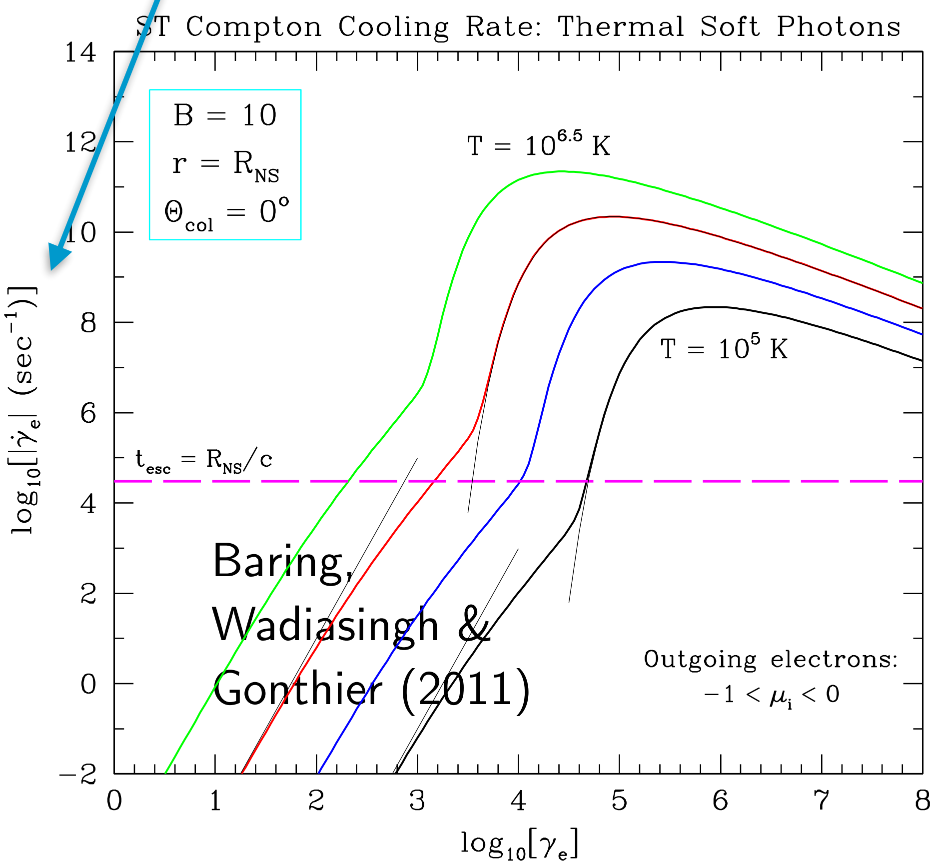
Conditions for FRBs from short bursts

- Resonant Compton drag must not interfere - photon densities cannot be too high

$$\dot{\gamma}_{e,\,\mathrm{burst}} \sim e/(m_e c)E \sim 10^{15.5} B_{14} \nu_{\mathrm{kHz}} \sigma_{-3} \lambda_4 \quad \mathrm{s}^{-1}$$

$$\gamma_{\max} \sim \frac{e\Delta\Phi_{\max}}{m_e c^2} \sim 10^9 \ \nu_{\mathrm{kHz}}\, \sigma_{-3}\, \lambda_4^2\, B_{14}$$





Baring, Wadiasingh & Gonthier (2011)

$$\gamma^{\mathrm{CR}}_{e,\mathrm{RRLA}} \approx 9 \times 10^7 \left(B_{14}\nu_{\mathrm{kHz}}\xi_1\rho^2_{c,7}\right)^{1/4}$$

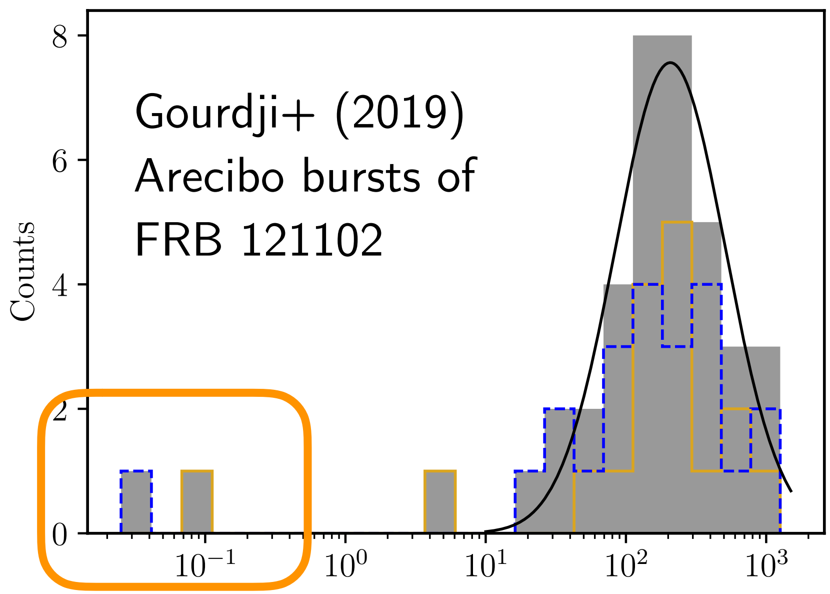
For typical parameters for crustal magnetic dislocations, efficient magnetic pair production requires surface B > 10^{12} - 10^{13} G for above-threshold pair production in CR RRLA

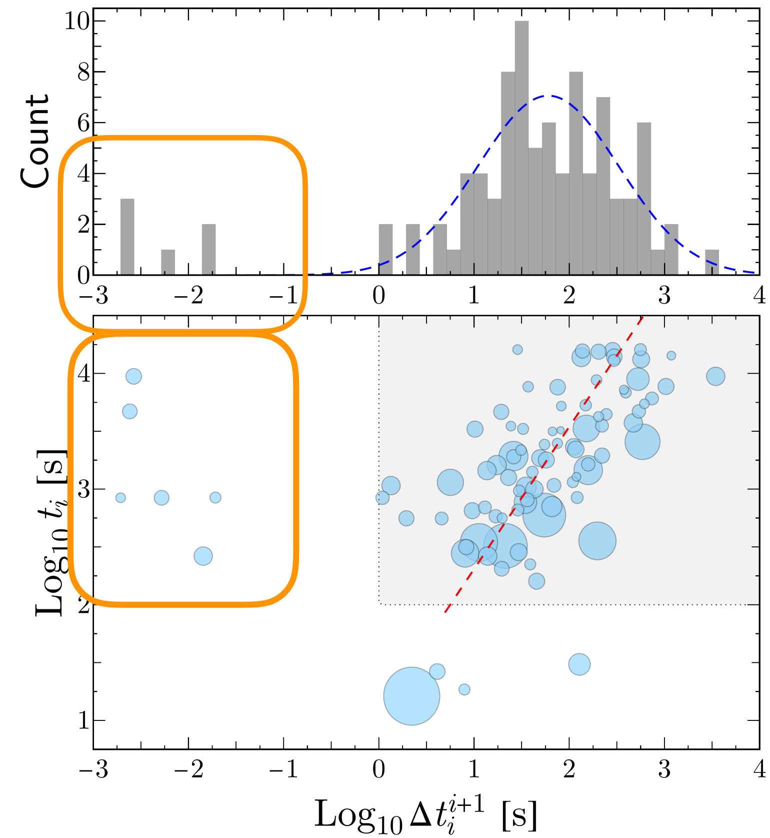
$$B \gtrsim 3 \times 10^{13} \left(\frac{\chi_0 \rho_{c,7}^{1/2}}{\xi_1^{3/4} h_1 \nu_{\mathrm{kHz}}^{3/4}}\right)^{4/7} \qquad \mathrm{G}$$

Minimum recurrence time

- Core-crust damping (e.g. Levin 2006) limits recurrences to within $\sim$ 1-2 s
- Interestingly, the longest cluster of repetitions in Zhang+ (2018) persists for 2 seconds
- Within this $\sim$ 1-2 s, the charges must clear a flux tube prior — the timescale of this is pair multiplicity times burst duration *for the critical/twist burst amplitude* $\rho_{\rm twist} \sim \rho_{\rm burst}$
- If burst amplitudes ξ are large enough, then recurrences may occur on crustal oscillation periods of 1-10 ms

$$\text{FRB recurrence time } \gtrsim 1/\nu_{\rm osc} \text{ or } \kappa\tau_{\rm ms}$$





Propagation Effects

- Vacuum birefringence is unimportant for radio frequencies
- The characteristic scale for both emission and propagation effects is the local plasma frequency

$$\nu_e \lesssim \frac{1}{\sqrt{2\pi}} \omega_B^{1/2}\, \sigma^{1/2}\, \nu_{\rm osc}^{1/2} \sim 17\, B_{14}^{1/2}\, \sigma_{-3}^{1/2}\, \nu_{\rm osc,\,kHz}^{1/2} \quad \mathrm{GHz}$$

- For 1 GHz emission, it must arise from about 7 R* or the plasma must be relativistic for transparency — both are plausible
- PA may be "frozen in" by "adiabatic walking" of the X-mode within about

$$\frac{r_{\rm fo}}{R_*} \lesssim 18\, B_{0,14}^{1/3}\, R_{B,7}^{1/3}\, a_{0,5}^{-1/3}\, \nu_{\rm em,GHz}^{-1/3}\, \sigma_{-3}^{1/3}\, \nu_{\rm osc,\,kHz}^{1/3}$$

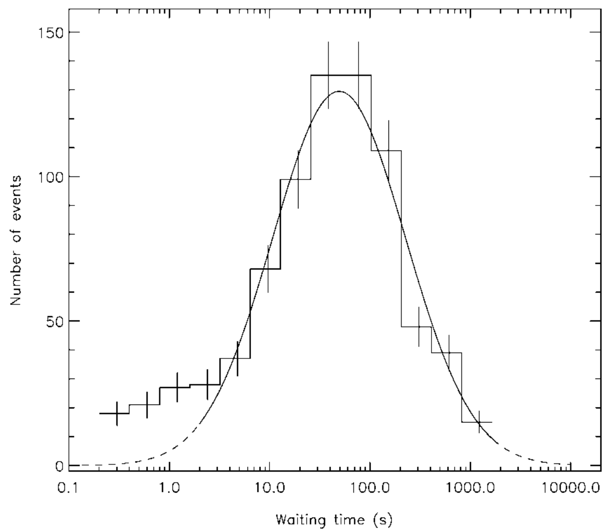
Summary and Outlook

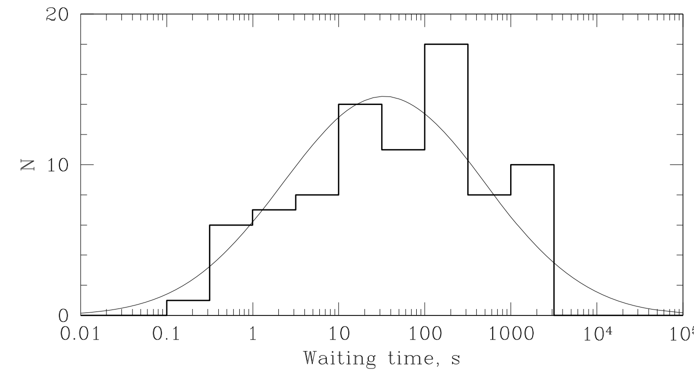
- Repeating FRBs like FRB 121102 are proposed to originate from magnetars undergoing crustal slippages which are known produce high-energy "magnetar short bursts"
- Most (>50%) FRBs ought to yield short bursts, but not all short bursts result in FRBs
- Future: time-coincidence confirmation for nearby FRBs with short bursts — must be very close O(1 Mpc) with current instruments
- PA variation $\rightarrow$ conditions are sufficient that adiabatic walking can occur of radio propagation, so PA variation could be driven by geometry
- Prediction: if bursts during slow heterogeneous untwisting, small DM variation may have the imprint of the rotator's period
- Prediction: find period in PA variation? Need a large (100s) sample of FRBs with PAs
- Prediction: QPOs in large samples burst repetition clusters?
- Prediction: Repetition clusters which persist beyond 1-2 s should be rare due to core-crust damping
- Prediction: Signals above a few MeV should not be seen in time-coincidence with FRBs (but a MWNe may be present)

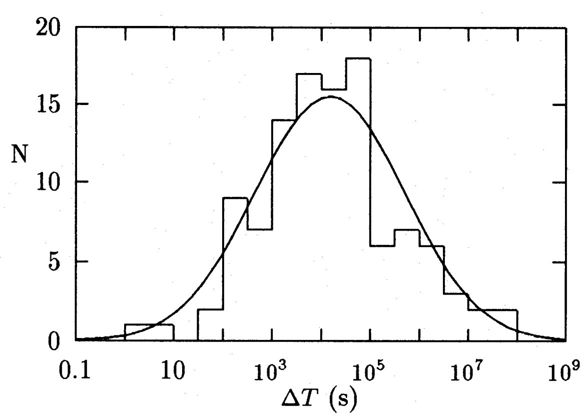
Backup Slides

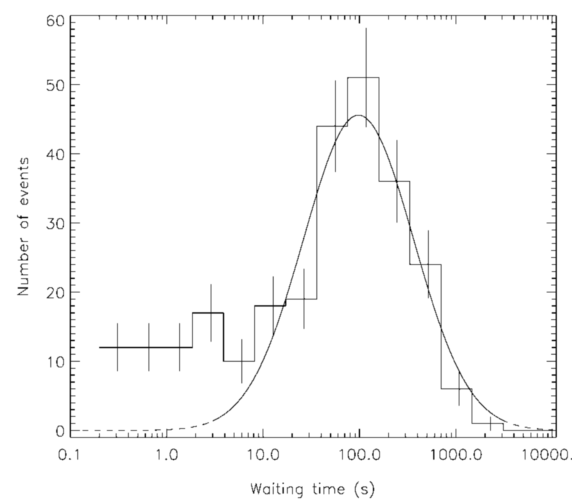
FRBs and “Magnetar Short Bursts”

- Lognormality is just a parabola in log-log (low-order approximation of a humped distribution at the peak)
- Lognormality of waiting times is observed in magnetar short bursts episodes → loguniform character in arrival time









The First Repeating FRB?

THE ASTROPHYSICAL JOURNAL, 236:L109–L113, 1980 March 15

DISCOVERY OF MILLISECOND RADIO BURSTS FROM M87

I. R. LINSCOTT AND J. W. ERKES[1]
Dudley Observatory, Schenectady, New York
Received 1979 August 10; accepted 1979 December 19

ABSTRACT

Highly dispersed radio pulses have been detected from M87 at radio frequencies of 430, 606, and 1420 MHz. The pulse sweep rates scale with the third power of the observing frequency as expected from the cold plasma law. The sweep rates correspond to dispersion measures in the range $1\text{–}5 \times 10^3$ parsec cm^{-3}. The pulses frequently appear grouped together separated within the group by approximately 50 ms. Peak power levels of 100 Jy and temporal widths of a few ms for individual pulses are found, and the group repetition rate is of the order of 1 s^{-1}.
Subject headings: galaxies: individual — radio sources: galaxies

Exhibited features associated with modern repeating FRBs:

- Millisecond duration
- Multiple repetitions in clusters
- Luminosity of 10^{40} erg/s
- Frequency drifts?

Unconfirmed in observations which followed, but these did not rule out episodic behavior

Frequency Drifts